Exo-Higgs at 750 GeV and Genesis of Baryons

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We propose that the diphoton excess at 750 GeV reported by ATLAS and CMS is due to the decay of an *exo-Higgs* scalar η associated with the breaking of a new $SU(2)_e$ symmetry, dubbed *exo-spin*. New fermions, *exo-quarks* and *exo-leptons*, get TeV-scale masses through Yukawa couplings with η and generate its couplings to gluons and photons at 1-loop. The matter content of our model yields a $B-L$ anomaly under $SU(2)_e$, whose breaking we assume entails a first order phase transition. A non-trivial $B-L$ asymmetry may therefore be generated in the early universe, potentially providing a baryogenesis mechanism through the Standard Model (SM) sphaleron processes. The spontaneous breaking of $SU(2)_e$ can in principle directly lead to electroweak symmetry breaking, thereby accounting for the proximity of the mass scales of the SM Higgs and the exo-Higgs. Our model can be distinguished from those comprising a singlet scalar and vector fermions by the discovery of TeV scale exo-vector bosons, corresponding to the broken $SU(2)_e$ generators, at the LHC.

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INTRODUCTION

The diphoton excess at the LHC, reported by both the ATLAS and CMS [1, 2] collaborations at about 750 GeV, has been the subject of a large number of papers over the past several months[1]. While the significance of the excess is not at the discovery level yet, its appearance in both experiments, persistence upon further analysis, and the nature of the final state provide some ground for cautious optimism that it may be a real signal of new physics. One is then compelled to ask what the underlying new physics can be.

Many ideas have been entertained and cover a multitude of possibilities[2]. However, among them, the possibility of a scalar resonance with a mass of 750 GeV, produced via gluon fusion and decaying into photons, both at 1-loop level, represents one of the most straightforward scenarios (See, for example, Refs. [3–7]). The gluon initial states are well-motivated, as their corresponding luminosity gets enhanced much more than that for the quarks with center of mass energy of collisions, greatly reducing tension with the LHC Run 1 data. Here, the particles that mediate the loop-generated couplings of the scalar are generally assumed to be heavy vector-like fermions that carry color and charge, as mediation by lighter states, such as those in the Standard Model (SM), would provide tree-level decay modes that would make the requisite diphoton signal strength hard to explain.

The above simple setup would then suffice to account for the key features of the excess, as they are currently known. However, one may then inquire how the new states may fit within a larger picture of particle physics. Obviously, this question could be answered in a variety of ways, depending on one's view of fundamental physics and its open problems.

In this work, we entertain the possibility that the 750 GeV resonance is a scalar remnant of a TeV-scale Higgs mechanism responsible for the spontaneous breaking of a new $SU(2)_e$ gauge symmetry that we refer to as *exo-spin* (*exo: outside*, in Greek). None of the SM fields carry $SU(2)_e$, however there are new fermions charged under this symmetry, as well as under the SM $SU(3)_c$ color and hypercharge $U(1)_Y$. We will refer to the new color charged fermions as *exo-quarks*, while those that only carry hypercharge are referred to as *exo-leptons*. These fermions get their masses through Yukawa coupling to a doublet *exo-Higgs* whose vacuum expectation value (vev) breaks the $SU(2)_e$ symmetry.

Our proposed setup is motivated by the natural assumption that a particle whose properties are reminiscent of the SM Higgs is perhaps best thought of as a Higgs boson that breaks a new symmetry (For a sample of works that consider a Higgs field interpretation of the excess, see Refs. [8–12]). The simplicity and minimal nature of the $SU(2)_e$ group make it a compelling choice, however we go a step further and will assume that it is responsible for generating the non-zero baryon asymmetry in the early universe, thereby addressing one of the main open questions in cosmology and particle physics. More specifically, we choose our exo-fermion quantum numbers such that $B-L$, with B baryon number and L lepton number, is *anomalous* under $SU(2)_e$. One can then envision that if $SU(2)_e$ breaking in the early universe entailed a *first order phase transition*, at a temperature $T \sim 1$ TeV, the associated departure from equilibrium could lead to the appearance of non-zero $B-L$ that would then get processed into the cosmic baryon asymmetry by the SM sphalerons [13] (see also Refs. [14–16]). This is similar to the scenarios envisioned for electroweak baryogenesis that would require a strongly first order electroweak phase transition, which is however not realized by the SM

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[1] A large number of papers have been written on this subject since the initial announcement of the excess, as can be seen from the citations of Refs. [1, 2]

[2] See footnote (1)

Higgs. We then require that the coupling of the $SU(2)_e$ be large enough that, while perturbative, would still lead to a first order phase transition.

In the heavy exo-fermion limit, the diphoton signal strength is largely a function of the vev of the exo-Higgs doublet, which can then be fixed. Hence, the exo-Higgs potential parameters can be obtained for a given signal strength. We will also assume that the the SM Higgs portal coupling with exo-Higgs generates the SM Higgs mass parameter after $SU(2)_e$ breaking. This not only reduces the number of input parameters in the model, but also provides an explanation of the relative proximity of the the Higgs and exo-Higgs masses. We will next introduce the ingredients of our model and discuss its potential relevance to baryogenesis.

THE MODEL

In this section we will describe the main features of our model. We assume the existence of a new gauge symmetry $SU(2)_e$, completely broken by a Higgs field η, under which the SM fermions are singlets. As per the usual Higgs mechanism, three degrees of freedom of η give masses to the three gauge bosons ω_1, ω_2 and ω_3 associated with $SU(2)_e$, while we identify the fourth with the 750 GeV resonance. Unlike in the SM, $\omega_{1,2,3}$ are degenerate in mass. We also introduce new fermions, charged under $SU(2)_e$ and the SM gauge group, that acquire mass through Yukawa couplings with the exo-Higgs η. Following the SM naming rule we call the fermions in a triplet of $SU(3)_c$ exo-quarks Ϙ (archaic Greek letter pronounced *Koppa*), and the fermions that are singlets of $SU(3)_c$ exo-leptons Λ. The choice of possible quantum numbers is limited by requiring that the theory is free of gauge anomalies. Since the exo-fermions are vector-like under the SM gauge group, freedom from anomalies is trivially satisfied for that sector and the only non-trivial anomalies are the Adler-Bell-Jackiw with one $U(1)_Y$ and two $SU(2)_e$ bosons and the Witten anomaly [17]. We found the following anomaly free choice of quantum numbers under $SU(2)_e \otimes SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ particularly interesting:

$$
\begin{aligned}
Ϙ_L &= (2,3,1,-\frac{1}{3}) \qquad (1)\\
Ϙ_R &= (1,3,1,-\frac{1}{3}) \quad (\times 2)\\
\Lambda_L &= (1,1,1,-1) \quad (\times 2)\\
\Lambda_R &= (2,1,1,-1),
\end{aligned}
$$

where for the upper (lower) component of a $Ϙ_L$ doublet we have a corresponding $Ϙ_R^\wedge$ ($Ϙ_R^\vee$). We adopt a similar notation for the Λ_R doublet. Note that, since the exo-fermions are always singlets under $SU(2)_L$, the $U(1)_Y$ charge coincide with the electric charge. Lastly, we consider three generations of exo-fermions, $Ϙ^{\{1,2,3\}}$ and $\Lambda^{\{1,2,3\}}$. This completes our definitions for the field content of our model.

The Lagrangian is the sum of three contributions:

$$
\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_e + \mathcal{L}_m, \qquad (2)
$$

where the first term is the SM Lagrangian without the Higgs doublet mass term $\mu_H^2 H^\dagger H$, the second is the Lagrangian of the exo-sector, and in the third we have the terms of mixing between SM and exo-sector. The second term of Eq. (2) is

$$
\begin{aligned}
\mathcal{L}_e &= -\frac{1}{4}\omega^a_{\mu\nu}\omega_a^{\mu\nu} + (D_\mu\eta)^\dagger(D^\mu\eta) + \mu_\eta^2\eta^\dagger\eta - \lambda_\eta|\eta^\dagger\eta|^2\\
&+ i\bar{Ϙ}_L \not{D} Ϙ_L + i\bar{Ϙ}_R \not{D} Ϙ_R + i\bar{\Lambda}_L \not{D}\Lambda_L + i\bar{\Lambda}_R \not{D}\Lambda_R\\
&- Y_{Ϙ}^{\vee;i,j}\eta\bar{Ϙ}^i_L Ϙ_R^{\vee;j} - Y_{Ϙ}^{\wedge;i,j}\tilde{\eta}\bar{Ϙ}^i_L Ϙ_R^{\wedge;j}\\
&- Y_\Lambda^{\vee;i,j}\eta\bar{\Lambda}^i_R\Lambda_L^{\vee;j} - Y_\Lambda^{\wedge;i,j}\tilde{\eta}\bar{\Lambda}^i_R\Lambda_L^{\wedge;j}, \qquad (3)
\end{aligned}
$$

plus the usual gauge fixing and Fadeev-Popov ghost terms. The indices i,j refer to different generations. As in the SM we can rotate the fields to a mass basis, and generate the exo-sector counter-parts of the CKM and PMNS matrices.

We now discuss the mixing terms. The mixing Lagrangian can be written in general as

$$
\begin{aligned}
\mathcal{L}_m &= 2k_{\eta H}\eta^\dagger\eta H^\dagger H \qquad (4)\\
&- Y^{\vee;i,j}_{Ϙq}\eta\,\bar{Ϙ}^i_L d^j_R - Y^{\wedge;i,j}_{Ϙq}\;\tilde{\eta}\,\bar{Ϙ}^i_L d^j_R\\
&- Y^{\vee;i,j}_{qϘ} H\bar{q}^i_L Ϙ^{\vee;j}_R - Y^{\wedge;i,j}_{qϘ} H\bar{q}^i_L Ϙ^{\wedge;j}_R\\
&- \mathcal{M}^{\wedge;i,j}_\Lambda\bar{\Lambda}^{\wedge;i}_L e^j_R - \mathcal{M}^{\vee;i,j}_\Lambda\bar{\Lambda}^{\vee;i}_L e^j_R,
\end{aligned}
$$

where q_L is the left-handed quark doublet, d_R is a right-handed down-type quark and e_R is a right-handed charged lepton. The first term of eq. (4) is the mixing between the Higgs fields of the two sectors (we will be interested in values of $k_{\eta H}^2 \ll \lambda_H\lambda_\eta$ and hence the negative sign of this interaction does not yield an unstable potential). We fix the value of $k_{\eta H}$ imposing that $k_{\eta H}v_\eta^2 = \mu_H^2$ where v_η is the vev of the η field, $\langle\eta\rangle = v_\eta/\sqrt{2}$, and $\mu_H = \sqrt{\lambda v_H^2}$ where v_H is the vev of the SM Higgs doublet. In this way, we can justify the proximity between the breaking scale of $SU(2)_e$ and the vev of SM Higgs doublet. This is not a requirement of our model, but the predicted value of $k_{\eta H}$ sits well within the phenomenological constraints, as we will see later.

In the second line of Eq. (1), $Ϙ_R$ has the same quantum numbers as a d_R, so it can couple to q_L with a Yukawa interaction mediated by the SM Higgs. In the same way d_R can couple to $Ϙ_L$ as shown in the second and third lines of Eq. (4). The Yukawa matrices will generically have off-diagonal terms, that can produce Flavor Changing Neutral Currents (FCNC). However, we can set the off-diagonal terms as small as we want without altering the main purpose of this work, and, for simplicity, we

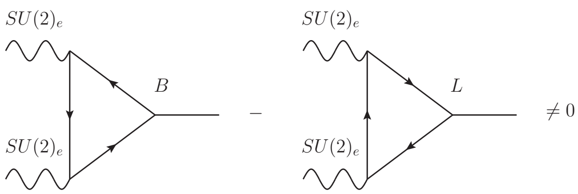

FIG. 1: Triangular anomaly for $B - L$. Although the field content of the exo-sector is similar to the one of the SM, the exo-leptons are right-handed doublets, so their contribution has a sign opposite to that of the exo-quarks.

will consider all the Yukawa matrices in Eq. (4) to be diagonal.

The lepton sector is peculiar since the quantum numbers of Λ_L allow us to write a mixing term where $\mathcal{M}_\Lambda$ is a mass parameter not directly related to the other scales of the theory (v_H and v_η). As we will see in the phenomenology section, its value should be at least one order of magnitude smaller than v_H. However, that relatively small value can be justified if this interaction descends from a higher energy theory where heavier degrees of freedom have been integrated out. As before, off-diagonal $\mathcal{M}_\Lambda$ terms can generate FCNC in the lepton sector, but we can assume $\mathcal{M}_\Lambda$ to be diagonal for the purposes of this paper.

The off-diagonal terms in the exo-quark Yukawa matrices in Eq. (3) can also be a source of FCNCs. However the mixing between SM-quarks and exo-quarks can be set small to avoid strong bounds on the CKM of the exo-sector. In any case, for simplicity, we will consider a limit where all the off-diagonal terms are zero, the elements of the same exo-doublet are degenerate in mass and two of the exo-quark generations have the same mass. It has to be noted, however, that in general a more complex Yukawa sector for the exo-quarks is desirable, since it can be a source of the extra CP-violation needed for baryogenesis. A similar reasoning applies to the exo-lepton sector, where we will set the Yukawa matrices diagonal and all the exo-leptons degenerate in the mass.

It is interesting to note that, at tree level, the Lagrangian in Eq. (2) preserves B and L, once we assign to the exo-quarks and the exo-leptons the quantum numbers $B = \frac{1}{3}$ and $L = 1$, respectively. However once we compute the triangular anomaly in Fig. 1, the resulting $B - L$ current is anomalous, while the $B + L$ is preserved.

CONNECTION TO COSMOLOGY

As discussed in the last section, $B - L$ number is anomalous under our $SU(2)_e$. In what follows, we will argue that this anomaly offers a possibility to address an important open question in cosmology, that is the origin of baryon asymmetry in the universe. To address this question, one needs to introduce a baryogenesis mechanism that satisfies Sakharov's criteria [18]: *(i)* baryon number violation, *(ii)* C and CP violation, and *(iii)* departure from equilibrium. In the SM, *(i)* is provided by sphaleron processes at temperatures $T \gtrsim 100$ GeV before spontaneous electroweak symmetry breaking. Both C and CP violation are present in the SM, but the amount of CP violation is too small. Condition *(iii)* would have required a first order electroweak phase transition, which is not feasible with the SM Higgs potential.

Various extensions of the SM have been proposed in order to supplement its shortcomings in the context of electroweak baryogenesis. In particular, one can entertain the possibility that an initial $B - L$ number, which is respected by all SM interactions, was present well before electroweak symmetry breaking took place. The SM sphalerons would then process the $B - L$ asymmetry into $\Delta B \neq 0$ and $\Delta L \neq 0$ asymmetries *in equilibrium*. A well-motivated scenario of this kind, referred to as *leptogenesis* [19], employs heavy Majorana neutrinos that are required to implement a seesaw mechanism for generating light SM neutrino masses. While an interesting idea, leptogenesis typically requires that Majorana states appear at scales $\gg 1$ TeV, well beyond the reach of direct discovery. Hence, this idea is only indirectly testable.

Here, we propose that the $B - L$ anomaly in our model can lead to the generation of $\Delta(B - L) \neq 0$ if $SU(2)_e$ breaking at $T \sim 1$ TeV involves a first order phase transition. This is in analogy with electroweak baryogenesis mechanisms, where a strong transition would have generated departure from equilibrium as required for a baryon asymmetry. The generation of a $B - L$ asymmetry would also require sources of CP violation, which our model would readily provide once generally complex Yukawa couplings are assumed. This motivates us to consider model parameters that support a first order $SU(2)_e$ phase transition. The key reason the SM cannot afford this possibility is that the finite temperature effective potential for the Higgs has a thermally generated *cubic* term that is too small. This term can lead to the appearance of a requisite barrier in the potential during the phase transition.

By analogy with the SM case, we see that the coefficient of the relevant cubic term for the $SU(2)_e$ transition is (see, for example, Ref. [20])

$$E = \frac{3\, m_\omega^3}{4\pi v_\eta^3} = \frac{3\, g_e^3}{32\pi}\,. \tag{5}$$

A strong first order phase transition is one whose order parameter at the critical temperature of the transition T_c satisfies $\eta(T_c)/T_c \gtrsim 1$, where $\eta(T_c)$ is the exo-Higgs field value at the local minimum of the effective potential for $T = T_c$. One can show [20] that this requirement then implies $2E/\lambda_\eta(T_c) \gtrsim 1$, where $\lambda_\eta(T_c)$ is the quartic self-coupling of the η at T_c.

Using the approximation $\lambda_\eta(T_c) \approx \lambda_\eta$, the condition for a strong first order phase transition in our model can then be written as

$$\frac{3\, g_e^3}{16\pi\, \lambda_\eta} \gtrsim 1\,. \tag{6}$$

Later, we will show that the signal strength suggested by the diphoton excess is, given our choice of model parameters and ingredients, mainly sensitive to $\langle \eta \rangle$. Hence, for a given signal strength, and assuming that the exo-Higgs mass is 750 GeV, one can determine λ_η within our setup. We can then use Eq. (6) to derive a lower bound on g_e, motivated by the possibility of explaining the baryon asymmetry of the universe, as explained above. Such a baryogenesis mechanism will have the great advantage of being testable at the LHC and future high energy colliders, given that it is based on physics at or near the TeV scale.

SIGNAL STRENGTH AND PARAMETERS

In this section, we will discuss the signal strength and its implications for our parameter space. All the cross sections, decay rates, and branching ratios, appearing in this and the next sections, are obtained using MadGraph5_aMC@NLO [21] and MadWidth [22] with a UFO model [23] made with the FeynRules package [24]. Loop-induced processes are computed following Ref. [25], and the corresponding counter term is computed with NLOCT [26]. In all simulations we use NNPDF2.3 parton distributions [27], except for the 750 GeV signal, where we use CT14nlo [28] to be consistent with Ref. [29], so that we can apply the NLO+NNLL K factor computed with the same setup.

The signal strength is mostly sensitive to the vev of the exo-Higgs doublet. Similarly to the SM, in the heavy fermion mass limit, the loop-induced $gg \to \eta$ and $\eta \to \gamma\gamma$ are described by the following dimension-five operators:

$$\mathcal{L} = \frac{\alpha_s}{3\pi v_\eta} N_{\text{♀}} \frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} \eta + \frac{2\alpha}{3\pi v_\eta} \sum_{\text{♀},\Lambda} N_c Q_f^2 \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \eta \tag{7}$$

With our setup, $v_\eta \sim 1$ TeV will roughly produce the observed signal strength. Other parameters, like mixing angles and exo-Yukawas, could also affect the signal strength, by modifying the decay modes of η and the fermion masses running in the loop.

To facilitate a more concrete discussion, let us consider the following benchmark point

$$\begin{array}{llll} v_\eta & = 1.2\,\text{TeV} & \text{Vev of the } \eta \text{ field} \\ m_{\text{♀}}^{>} & = 800\,\text{GeV} & \text{Mass of the heavier ♀} \\ m_{\text{♀}}^{<} & = 500\,\text{GeV} & \text{Mass of the lighter ♀'s} \\ m_\Lambda & = 380\,\text{GeV} & \text{Mass of } \Lambda\text{'s} \\ \mathcal{M}_\Lambda & = 1\,\text{GeV} & \Lambda - l \text{ mixing mass parameter} \\ \theta^{\text{♀}}_{L,R} & = 10^{-3} & \text{♀} - q \text{ mixing angles} \\ g_e & = 2 & SU(2)_e \text{ gauge coupling} \end{array} \tag{8}$$

With these parameters, we find that the cross section for the 750 GeV signal is about 4.1 fb, taking into account an NLO+NNLL K factor of 1.56 from Ref. [29]. This value should be compared with the weighted average deduced from the ATLAS [1] and CMS [2] data 4.6 ± 1.3 fb.

Mode	BR
gg	82.1%
W^+W^-	7.4%
HH	4.2%
ZZ	3.7%
$t\bar{t}$	1.8%
$\gamma\gamma$	0.81%
γZ	0.47%
$l\Lambda$	0.12%
Γ_η	0.060 GeV

TABLE I: Main branching ratios and the total width Γ_η of the exo-Higgs η. Channels with lower than 0.01% branching ratio are not displayed. The values in the table correspond to the benchmark point in Eq. (8).

The $2k_{\eta H}\eta^\dagger\eta H^\dagger H$ term induces a mixing between H and η. With our assumption, namely that v_η provides the μ_H term of the SM and leads to electroweak symmetry breaking, this mixing is about $\sin\theta_{\eta H} = 0.006$. As a consequence, η could decay to SM particles, such as W^+W^-, ZZ, $t\bar{t}$, and HH, through the Higgs portal, and these channels can be searched for in the future. They also affect the value of v_η, by diluting our signal strength by about $\sim 15\%$. With mixing higher than this value it will be difficult to achieve the desired signal strength, so in this sense $\theta_{\eta H}$ is bounded from above.

The main branching fractions of η and its total width Γ_η are given in Table I. We find that the implied signal strengths for these channels are not in conflict with existing constraints from the LHC Run 1 data. As can be seen from the table, the branching fraction for $\eta \to ZZ$ and WW are, respectively, ~ 4 and ~ 9 times larger than that for the diphoton channel. Note that in many minimal models the signal is obtained by coupling a singlet scalar, which is unmixed with the SM Higgs, to vector fermions carrying only color and hypercharge. Then, the ZZ coupling to η is loop induced and sub-dominant to the $\gamma\gamma$ coupling, due to suppression by $\tan^2\theta_W$, where θ_W is the weak mixing angle. In such models, one does

not expect any significant branching ratio into the WW final state.

The presence of significant ZZ and WW branching fractions for η in our model can then provide an interesting signal of Higgs-η mixing that can be accessible in the LHC Run 2. In particular, a measurement of the ratio of BR($\eta \to ZZ$) to BR($\eta \to \gamma\gamma$), given the value of the diphoton signal strength, can yield the amount of Higgs-η mixing. Also, if the coupling of η to Z and W is dominated by the Higgs portal, then in general

$$\frac{\mathrm{BR}(\eta \to WW)}{\mathrm{BR}(\eta \to ZZ)} \approx 2. \tag{9}$$

This can then provide a test of our assumption regarding the induced Higgs mass parameter from $\langle \eta \rangle \neq 0$.

With our benchmark parameters, the mass of the two $\Qoppa$'s in the third generation, $m_{\Qoppa}^{>}$, is set heavy to satisfy the bound from vector-like quark searches. The $\Qoppa$'s decay through three channels, $\Qoppa \to tW^-$, $\Qoppa \to bZ$, and $\Qoppa \to bH$, with branching ratios of $\sim 50\%$, $\sim 25\%$, and $\sim 25\%$, respectively. For small mixing between $\Qoppa$ and quark, the individual decay rates are roughly proportional to $\sin^2 \theta_L^{\Qoppa}$, where $\theta_L^{\Qoppa}$ is the mixing angle between $\Qoppa_L$ and b_L, so the three branching ratios are roughly constant. Given these values, the bound on vector-like quark masses is 790 GeV [30], therefore we set $m_{\Qoppa}^{>}$ to be 800 GeV.

The masses of the $\Qoppa$'s in the first two generations have to be heavier than half of the η mass, to avoid the $\eta \to \Qoppa\bar{\Qoppa}$ decay suppressing the signal. Apart from that, these lighter exo-quarks are not subject to severe constraints as they mainly decay to Wj, Zj and Hj. One relevant search channel is stop pair production, with each stop decaying into a charm quark and a neutralino [31]. The exo-quarks could decay through $\Qoppa \to Zj \to j$+MET which has the same signal, but for our benchmark parameters the cross sections are $1 \sim 2$ orders of magnitude below the uncertainty from the background.

The Λ masses do not have severe bounds either [32], except that they should be again larger than $m_\eta/2$. We set them at 380 GeV, nearly one half of the exo-Higgs mass, mainly to enhance the signal and keep v_η well above 1 TeV. This is however not a strict requirement. For example, $m_\Lambda \sim 420$ GeV is still feasible with a somewhat larger g_e.

Once v_η is fixed, $\lambda_\eta = 0.20$ can be derived, and Eq. (6) requires $g_e > 1.48$. We choose $g_e = 2$ to be well inside the region of parameters favored by a strong first order phase transition. This value then sets the mass of ω vector bosons, $m_\omega = 1.2$ TeV. As we will see later, with this mass ω production at LHC 7 and 8 TeV runs is too suppressed to yield a significant signal. However, the Run 2 of the LHC will have a chance to discover the ω bosons.

The mixing angles between $\Qoppa$'s and quarks should be well below $\mathcal{O}(1\%)$, so that $\eta \to q\bar{\Qoppa}, \Qoppa\bar{q}$ decay rates will not affect the signal strength too much. Apart from this

Mode	$\Lambda^{\wedge,\vee;1}$	$\Lambda^{\wedge,\vee;2}$	$\Lambda^{\wedge,\vee;3}$
Hl	100%	84.0%	22.0%
$W^-\nu$	$\sim 10^{-6}$	10.6%	52.1%
Zl	$\sim 10^{-6}$	5.3%	25.9%

TABLE II: Λ branching ratios.

condition, the phenomenology does not depend much on the value of these mixing angles. Since the $\Qoppa$ mixing sector has two kinds of mixing terms, $\bar{\Qoppa}_L q_R$ and $\bar{q}_L \Qoppa_R$, the left- and right-handed mixing angles are in principle independent of each other. We notice that for a mixing angle less than $O(10^{-7})$, the exo-quark would decay with a displaced vertex. We choose $\theta_{L,R}^{\Qoppa} = 10^{-3}$ for simplicity.

The mixing between Λ's and leptons is different: the $\mathcal{M}_\Lambda$ terms could couple Λ_L to l_R, but mass couplings from Λ_R to l_L are not allowed. As a result, the left handed mixing angle, θ_L^Λ, is suppressed by the lepton mass:

$$\frac{\tan \theta_L^\Lambda}{\tan \theta_R^\Lambda} = \frac{m_l}{m_\Lambda}. \tag{10}$$

We choose $\mathcal{M}_\Lambda = 1$ GeV, corresponding to $\theta_R^\Lambda \approx 2.7 \times 10^{-3}$ for all three generations. Note that with this choice, the left-handed mixing angle between the electron and $\Lambda^{\wedge,\vee;1}$ is extremely tiny, $\sim 3.6 \times 10^{-9}$. If $\mathcal{M}_\Lambda \gtrsim 10$ GeV the signal strength will be affected at $\mathcal{O}(10\%)$ level by $\eta \to l\Lambda$, while if $\mathcal{M}_\Lambda \lesssim 0.1$ GeV Λ will decay with a displaced vertex.

With our choice of benchmark parameters, the dominant decay channel for $\Lambda^{\wedge,\vee;1}$ and $\Lambda^{\wedge,\vee;2}$ is $\Lambda^{\wedge,\vee;i} \to H + l_i$ where $i = 1, 2$ is the flavor index. If $\theta_{\eta H} = 0$, the branching ratios of the three possible decay channels, $\Lambda^{\wedge,\vee;i} \to W^- + \nu_i$, $\Lambda^{\wedge,\vee;i} \to Z + l_i$, and $\Lambda^{\wedge,\vee;i} \to H + l_i$, are roughly 50%, 25%, and 25%, respectively. However the first two decay modes, $W^- + \nu$ and $Z + l$, occur through only left-handed mixing θ_L^Λ, which is suppressed by m_l/m_Λ. This is because the right handed Λ and l only couple to the hypercharge boson, with the same hypercharge, so a unitary rotation between Λ and l will not generate any off-diagonal coupling. On the other hand, the last decay channel $\Lambda \to H + l$ occurs through the first diagram in Fig. 2, and is also suppressed by m_l because of the lepton Yukawa. As a result the decay rate of $\Lambda^{\wedge,\vee;1}$ is below 10^{-13} GeV and would lead to displaced vertex. However, with a nonzero $\theta_{\eta H}$, the leptons can decay through the last diagram in Fig. 2. Even though the diagram involves two mixing angles θ_R^Λ and $\theta_{\eta H}$, for electron and muon this is still the dominant channel. As a result, $\Lambda^{\wedge,\vee;1,2}$ mostly decay to Higgs and lepton. The branching ratios of all three exo-leptons are given in Table II.

It is interesting to see that the lighter lepton has a larger branching ratio to the Higgs. The corresponding rate for $\Lambda^{\wedge,\vee;1}$ is about 7×10^{-11} GeV, above the limit for displaced vertex.

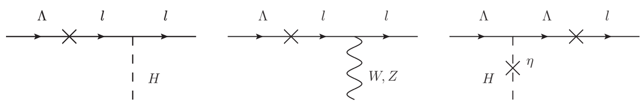

FIG. 2: Decays of a Λ into a leptons. The decay into τ is mostly mediated by the first two processes, while the decays into μ and e are mostly mediated by the third, since the first two are suppressed by m_e and m_μ.

Our assumption, that v_η leads to the electroweak symmetry breaking of the SM, gives the right amount of $\eta - H$ mixing, that is enough to give a reasonable decay rate for Λ, but is not too large to dilute the signal through the Higgs portal.

PREDICTIONS

In this section, we will discuss the predictions and collider signals of our model that can be looked for in the future. Within our mode, we predict new heavy quarks and leptons, i.e., Ϙ and Λ, that are vector-like under the SM symmetries but chiral under the exo group. The decay modes of Ϙ's are $Ϙ^{\wedge,\vee;3} \to bZ, bH, tW^-$, $Ϙ^{\wedge,\vee;1,2} \to jZ, jH, jW^-$, and of Λ's are $lZ, lH, \nu_l W^-$. In this sense they are fairly standard vector-like fermions, and can be discovered in corresponding searches. This is similar to many other models that use vector-like fermions to explain the 750 GeV resonance.

The more distinct signature of our model is the production of the exo-gauge bosons, i.e. $\omega^\uparrow$, $\omega^\downarrow$ (defined respectively as $(\omega^1 - i\omega^2)/\sqrt{2}$ and $(\omega^1 + i\omega^2)/\sqrt{2}$) and ω^3. The main production channel is through Ϙ-loop induced processes, $gg \to \omega\omega$ and $gg \to \omega j$. Note that the latter actually vanishes with our choice of parameters: the $Ϙ^\wedge$ and $Ϙ^\vee$ masses are set to be equal, but the loop has a trace over the T^3 generator in the exo-group, so their contributions cancel each other. Therefore to give a reasonable estimate on the cross section, we increase the $Ϙ^\wedge$ masses by 300 GeV, only for this process. The cross sections we found are in Table III. Note that the exo-gauge bosons could be produced also at the tree level, through $q\bar{q} \to \omega$, or $qg \to \omegaϘ$. However the first is suppressed by $(\theta^Ϙ_{L,R})^4$ and the second is by $(\theta^Ϙ_{L,R})^2$, and the resulting cross sections are negligible with $\theta^Ϙ_{L,R} \lesssim 10^{-2}$.

Process	8 TeV	13 TeV	14 TeV
$gg \to \omega^3 j$	0.016 fb	0.16 fb	0.26 fb
$gg \to \omega\omega$	0.003 fb	0.11 fb	0.17 fb

TABLE III: Cross sections of the main production channels at different energies. The double omega production sums over all exo-vector bosons.

From Table III, we can see that currently available LHC data should contain less than one ω; at 14 TeV, however, with 300 fb^{-1} accumulated luminosity we can have $\mathcal{O}(10^2)$ ω's produced. Even though the $\omega^3 j$ production has a higher cross section, it depends on the mass splitting. We therefore focus on the pair production of ω^3 and $\omega^\updownarrow$, which is our robust prediction. Consider the leptonic decay channel of ω, *e.g.* $\omega^3 \to \Lambda^{\wedge,\vee;i+}\Lambda^{\wedge,\vee;i-}$, where $i = 1, 2$ is the flavor index, the total branching ratio is 28.8%; $\omega^\updownarrow$ will decay into $\Lambda^{\wedge,\vee;+}\Lambda^{\vee,\wedge;-}$, but will not change the counting. Using the cross section given in Table III, we will end up with $0.17 \times 300 \times 28.8\%^2 = 4.2$ events with four Λ's given 300 fb^{-1} of accumulated luminosity . Among these events, $\Lambda^{\wedge,\vee;1}$ decays to the electron and Higgs boson $\sim 100\%$ of the time, while $\Lambda^{\wedge,\vee;2}$ decays to the muon plus H/Z with $\sim 90\%$ branching ratio in total. Therefore we will have 3.5 signal events containing four leptons coming from the decay of Λ's, with a typical p_T around $100 \sim 200$ GeV, and some additional jets or leptons from H or Z decays.

These events with four hard leptons are significant enough that they will not be missed. We estimate that the irreducible SM background, from four leptons with four Higgs/Z bosons, is negligible. Other background sources, for example those from $tt\bar{t}\bar{t}$ in all-leptonic channels, can be removed by requiring $p_T(l) > p_{Tcut}$, and $p_{Tcut} \approx 80$ GeV can already remove more than 98% of the background (that is with less than 0.1 event left), while reducing the signal by about 30%. The analysis can be further elaborated by requiring no missing transverse energy or requiring additional j/l, which will bring down the background by another $1 \sim 2$ orders of magnitude. In general, $4l$ production from the SM, after removing opposite-sign same-flavor lepton pairs coming from Z's and requiring $p_T(l) > 80$ GeV, is also below one event, and will become negligible once additional jets are required.

We can also consider tagging the b's from Higgs decay, which makes our signal even more distinguishable. Considering $\Lambda \to lH$ only, we will have about 3.1 $4H4l$ events at 300 fb^{-1}. If we require two of the four Higgs bosons decay to $b\bar{b}$ and tag four b's, we will have $2 \sim 3$ signal events with 4 b's, 4 hard leptons, and additional jets/leptons from Higgs decay. This is an even more distinct signal that can discriminate our model from other new physics scenarios, and is essentially free of background.

Of course, if the 750 GeV signal is confirmed, dedicated analysis will be needed to optimize the search strategy and to give a reliable estimate of the discovery potential, but the simple estimation described above already shows that the ω pair production is a promising channel.

DISCUSSIONS

The model we have considered in this work contains a number of new fields that have significant interaction

strengths. Hence, one may worry about quantum effects of these fields on the validity of the underlying model. We will denote by $\bar{\mu}$ the maximum energy scale beyond which our model would need further completion to avoid loss of theoretical control. In Fig. 3, we present various regimes of the model in the $y_{♀} - g_e$ plane, where $y_{♀}$ is the Yukawa coupling of the heaviest exo-quarks (800 GeV in our benchmark set of parameters). Here, we choose $\bar{\mu} = 10^5$ TeV, for which any unwanted effects of higher dimension operators from ultraviolet (UV) completions of our model are expected to be quite suppressed.

For $\bar{\mu} = 10^5$ TeV, our model maintains stability ($\lambda_\eta > 0$) and perturbative reliability (no Landau poles) in the green shaded area ("Stability"). The red area ("Instability") has $\lambda_\eta < 0$ and leads to an unstable exo-Higgs potential, whereas the yellow region ("Non-perturbativity") entails Landau poles for either λ_η or $y_{♀}$. The lower part of the plot, the horizontal band shaded gray, is disfavored if one requires a strong first order $SU(2)_e$ phase transition.

The region of "Stability" (green), as can be seen from Fig. 3, represents a significant part of the parameter space and does not require very special choices for a reliable model. It is also interesting that this region basically coincides with that favored by the requirement of a strong first order phase transition, as motivated by an explanation of the baryon asymmetry in the universe. This is related to the fact that the stability of the exo-Higgs quartic coupling gets enhanced by the contributions of ω gauge fields, which grow with larger g_e. We also add that gravitational waves corresponding to a strong phase transition at a temperature $T \sim 1$ TeV, as assumed in our scenario for baryogenesis, are typically predicted to be observable by future space-based gravitational waved detectors [33], such as LISA (for recent work on this topic, see for example Ref. [34]).

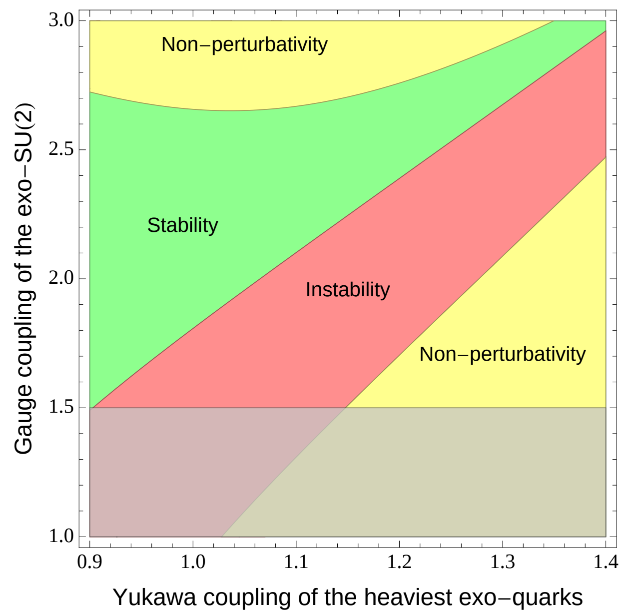

FIG. 3: The green area represents points in the $y_{♀} - g_e$ plane where all the parameters of the model stay positive and perturbative up to $\bar{\mu} = 10^5$ TeV. For the points in the red area λ_η crosses zero before $\bar{\mu}$. The points in the yellow region give a Landau-Pole for either λ_η or $y_{♀}$. The grey area is excluded if we require a first-order transition

CONCLUSIONS

In this work, we have proposed that the diphoton excess at 750 GeV, reported by the ATLAS and CMS collaborations, can be due to a scalar resonance that is the remnant of an $SU(2)_e$ exo-spin gauge symmetry breaking through the vev of an exo-Higgs doublet. We assume that there are exo-fermions, carrying SM color and hypercharge, that get their masses from the exo-Higgs mechanism and mediate the gluon fusion production and diphoton decays of the scalar.

We choose the matter content (exo-quarks and exo-leptons) and their associated quantum numbers such that $B - L$ is anomalous under $SU(2)_e$. Hence, with the assumption of a strong first order phase transition, one may expect the generation of a non-zero $B - L$ asymmetry in the early universe that can be the origin of the cosmic baryon asymmetry. This mechanism will then have the advantage of being testable at the TeV energies available at the LHC and future colliders, unlike those scenarios that originate from much higher scales. We have also assumed that the coupling of the exo-Higgs and SM Higgs doublets leads to the generation of the SM Higgs mass parameter, once $SU(2)_e$ is broken. This can explain the similar sizes of the exo-Higgs and SM Higgs mass scales, and allows η to have tree level decays into tt, WW and ZZ.

While the main ingredients of our model employed in explaining the diphoton excess effectively resemble those of models with a singlet scalar and vector-like fermions, the presence of TeV-scale vector bosons, corresponding to the broken generators of $SU(2)_e$, is a distinct prediction of our proposal. We find that double vector boson production, the most robust prediction of our scenario, can lead to a discovery of these states with about 300 fb^{-1} at the 14 TeV LHC. The decay of each vector boson dominantly produces two hard leptons, as well as two or more b-jets and more leptons and light jets, and can hence yield signals that are effectively background free. Under some mild assumptions about the spectrum of the model, single exo-vector boson production is also a viable discovery channel in the LHC Run 2.

The model we have studied can be valid up to very large scales of $\sim 10^5$ TeV, for typical choices of parameters. This scale is sufficiently large that any unwanted contributions from a UV completion can be negligibly suppressed. We also pointed out that the requirement of

strong phase transition at a temperature of order 1 TeV implies gravitational wave signals for our model that may be potentially detectable by future space-based missions, such as LISA.

Speramus Naturam, vel lectorem, notionibus nostris benignam esse.

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[1] The ATLAS Collaboration, *Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, (2015).

[2] CMS Collaboration, *Search for new physics in high mass diphoton events in* 3.3 fb^{-1} *of proton-proton collisions at* $\sqrt{s} = 13$ TeV *and combined interpretation of searches at* 8 TeV *and* 13 TeV, (2016).

[3] S. Knapen, T. Melia, M. Papucci, and K. Zurek, *Rays of light from the LHC*, Phys. Rev. **D93**, 075020 (2016), arXiv:1512.04928 [hep-ph].

[4] R. Franceschini, G. F. Giudice, J. F. Kamenik, M. McCullough, A. Pomarol, R. Rattazzi, M. Redi, F. Riva, A. Strumia, and R. Torre, *What is the $\gamma\gamma$ resonance at 750 GeV?*, JHEP **03**, 144 (2016), arXiv:1512.04933 [hep-ph].

[5] S. D. McDermott, P. Meade, and H. Ramani, *Singlet Scalar Resonances and the Diphoton Excess*, Phys. Lett. **B755**, 353 (2016), arXiv:1512.05326 [hep-ph].

[6] A. Falkowski, O. Slone, and T. Volansky, *Phenomenology of a 750 GeV Singlet*, JHEP **02**, 152 (2016), arXiv:1512.05777 [hep-ph].

[7] D. Aloni, K. Blum, A. Dery, A. Efrati, and Y. Nir, *On a possible large width 750 GeV diphoton resonance at ATLAS and CMS*, (2015), arXiv:1512.05778 [hep-ph].

[8] A. Angelescu, A. Djouadi, and G. Moreau, *Scenarii for interpretations of the LHC diphoton excess: two Higgs doublets and vector-like quarks and leptons*, Phys. Lett. **B756**, 126 (2016), arXiv:1512.04921 [hep-ph].

[9] R. S. Gupta, S. Jäger, Y. Kats, G. Perez, and E. Stamou, *Interpreting a 750 GeV Diphoton Resonance*, (2015), arXiv:1512.05332 [hep-ph].

[10] S. Chang, *A Simple $U(1)$ Gauge Theory Explanation of the Diphoton Excess*, Phys. Rev. **D93**, 055016 (2016), arXiv:1512.06426 [hep-ph].

[11] K. Kaneta, S. Kang, and H.-S. Lee, *Diphoton excess at the LHC Run 2 and its implications for a new heavy gauge boson*, (2015), arXiv:1512.09129 [hep-ph].

[12] M. Duerr, P. Fileviez Pérez, and J. Smirnov, *New Forces and the 750 GeV Resonance*, (2016), arXiv:1604.05319 [hep-ph].

[13] J. A. Harvey and M. S. Turner, *Cosmological baryon and lepton number in the presence of electroweak fermion number violation*, Phys. Rev. **D42**, 3344 (1990).

[14] J. Shu, T. M. P. Tait, and C. E. M. Wagner, *Baryogenesis from an Earlier Phase Transition*, Phys. Rev. **D75**, 063510 (2007), arXiv:hep-ph/0610375.

[15] K. Agashe, D. Kim, M. Toharia, and D. G. E. Walker, *Distinguishing Dark Matter Stabilization Symmetries Using Multiple Kinematic Edges and Cusps*, Phys. Rev. **D82**, 015007 (2010), arXiv:1003.0899 [hep-ph].

[16] D. G. E. Walker, *Dark Baryogenesis*, (2012), arXiv:1202.2348 [hep-ph].

[17] E. Witten, *An SU(2) Anomaly*, Phys. Lett. **B117**, 324 (1982).

[18] A. D. Sakharov, *Violation of CP Invariance, c Asymmetry, and Baryon Asymmetry of the Universe*, Pisma Zh. Eksp. Teor. Fiz. **5**, 32 (1967), [Usp. Fiz. Nauk161,61(1991)].

[19] M. Fukugita and T. Yanagida, *Baryogenesis Without Grand Unification*, Phys. Lett. **B174**, 45 (1986).

[20] M. Quiros, *Finite temperature field theory and phase transitions*, in *High energy physics and cosmology. Proceedings, Summer School, Trieste, Italy, June 29-July 17, 1998* (1999) pp. 187–259, arXiv:hep-ph/9901312.

[21] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, *et al.*, *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, JHEP **1407**, 079 (2014), arXiv:1405.0301 [hep-ph].

[22] J. Alwall, C. Duhr, B. Fuks, O. Mattelaer, D. G. Öztürk, and C.-H. Shen, *Computing decay rates for new physics theories with FeynRules and MadGraph5_aMC@NLO*, Comput. Phys. Commun. **197**, 312 (2015), arXiv:1402.1178 [hep-ph].

[23] C. Degrande, C. Duhr, B. Fuks, D. Grellscheid, O. Mattelaer, and T. Reiter, *UFO - The Universal FeynRules Output*, Comput. Phys. Commun. **183**, 1201 (2012), arXiv:1108.2040 [hep-ph].

[24] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, *FeynRules 2.0 - A complete toolbox for tree-level phenomenology*, Comput. Phys. Commun. **185**, 2250 (2014), arXiv:1310.1921 [hep-ph].

[25] V. Hirschi and O. Mattelaer, *Automated event generation for loop-induced processes*, JHEP **10**, 146 (2015), arXiv:1507.00020 [hep-ph].

[26] C. Degrande, *Automatic evaluation of UV and R2 terms for beyond the Standard Model Lagrangians: a proof-of-principle*, Comput. Phys. Commun. **197**, 239 (2015), arXiv:1406.3030 [hep-ph].

[27] R. D. Ball, V. Bertone, S. Carrazza, L. Del Debbio, S. Forte, A. Guffanti, N. P. Hartland, and J. Rojo (NNPDF), *Parton distributions with QED corrections*, Nucl. Phys. **B877**, 290 (2013), arXiv:1308.0598 [hep-ph].

[28] S. Dulat, T.-J. Hou, J. Gao, M. Guzzi, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump, and C. P. Yuan, *New parton distribution functions from a global analysis of quantum chromodynamics*, Phys. Rev. **D93**, 033006 (2016), arXiv:1506.07443 [hep-ph].

[29] X. Liu and H. Zhang, *RG-improved Prediction for 750 GeV Resonance Production at the LHC*, (2016), arXiv:1603.07190 [hep-ph].

[30] V. Khachatryan *et al.* (CMS), *Search for pair-produced vectorlike B quarks in proton-proton collisions at $\sqrt{s}$=8??TeV*, Phys. Rev. **D93**, 112009 (2016), arXiv:1507.07129 [hep-ex].

[31] CMS Collaboration, *Search for top squarks decaying to*

a charm quark and a neutralino in events with a jet and missing transverse momentum, (2014).

[32] G. Aad *et al.* (ATLAS), *Search for heavy lepton resonances decaying to a Z boson and a lepton in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, JHEP **09**, 108 (2015), arXiv:1506.01291 [hep-ex].

[33] C. Grojean and G. Servant, *Gravitational Waves from Phase Transitions at the Electroweak Scale and Beyond*, Phys. Rev. **D75**, 043507 (2007), arXiv:hep-ph/0607107.

[34] P. Schwaller, *Gravitational Waves from a Dark Phase Transition*, Phys. Rev. Lett. **115**, 181101 (2015), arXiv:1504.07263 [hep-ph].